JUPITER SYSTEM DATA ANALYSIS PROGRAM

Mechanisms, Manifestation, and Implications of Cryomagmatism on Europa

SUMMARY OF RESEARCH

Principal Investigator: Sarah A. Fagents

Arizona State University
Department of Geological Sciences
Box 871404
Tempe, AZ 85287-1404

Now at: HIGP/SOEST
University of Hawaii at Manoa
2525 Correa Road
Honolulu, HI 96822
fagents@hawaii.edu
(808) 956 3163

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1. Introduction

The objectives of the work completed under NASA Grant NAG5-8898 were (i) to document and characterize the low-albedo diffuse surfaces associated with triple bands and lenticulae, (ii) to determine their mechanisms of formation, and (iii) to assess the implications of these features for the resurfacing (in space and time) of the Europa and the nature of the Europan interior.

The approach involved a combination of processing and analysis of Solid State Imaging data returned by the Galileo spacecraft during the primary and extended mission phases, together with numerical modeling of the physical processes interpreted to be responsible for the formation of the observed features.

Figure 1. Galileo image number s0466664178, from orbit E17, resolution is ~220 m/pxl, field of view is ~150 km, north is up.

Triple bands (e.g., Fig. 1) were first identified in Voyager images of Europa [*Lucchitta and Soderblom*, 1982], and consist of a bright medial lineament flanked by dark margins. Origins proposed for these features included block faulting and flooding by water or slush [*Buratti and Golombek*, 1988], and intrusion and subsequent dehydration of hydrated minerals [*Finnerty et al.*, 1981]. However, Galileo images revealed that the outer edges of the dark margins were diffuse, which thus precluded the previously proposed origins, as they would have produced well-defined margins. Furthermore, the bright interior was shown to consist of pairs of ridges, which have to be explained by any model of formation. Also revealed by Galileo data were circular to lenticular dark spots and dark halos surrounding domes and pits.

Galileo-era origins proposed for these dark features include: release of liquid (water or brines) from the subsurface and low-viscosity flooding of topographic lows [*Greenberg et al.*, 1998; *Head and Pappalardo*, 1999]; cryoclastic deposits associated with vent of droplet sprays and impurities from a subsurface liquid body or layer [*Greeley et al.*, 1998]; subsurface intrusions of warm material causing thermal changes in the structure of surface ice leading to darkening (lag deposit formation or annealing) [*Fagents et al.*, 2000].

Based on the detailed geological characteristics of these features, the latter two explanations appear more plausible possibilities, so we explored these in detail under this work. If the deposits are cryoclastic, their sizes have implications for the amount of dissolved volatiles in the liquid layer. If they are thermally produced features (via cryomagmatic intrusions), the surface deposit sizes yield information on the intrusion geometry and temperature. Either case provides information on the state of the Europan interior.
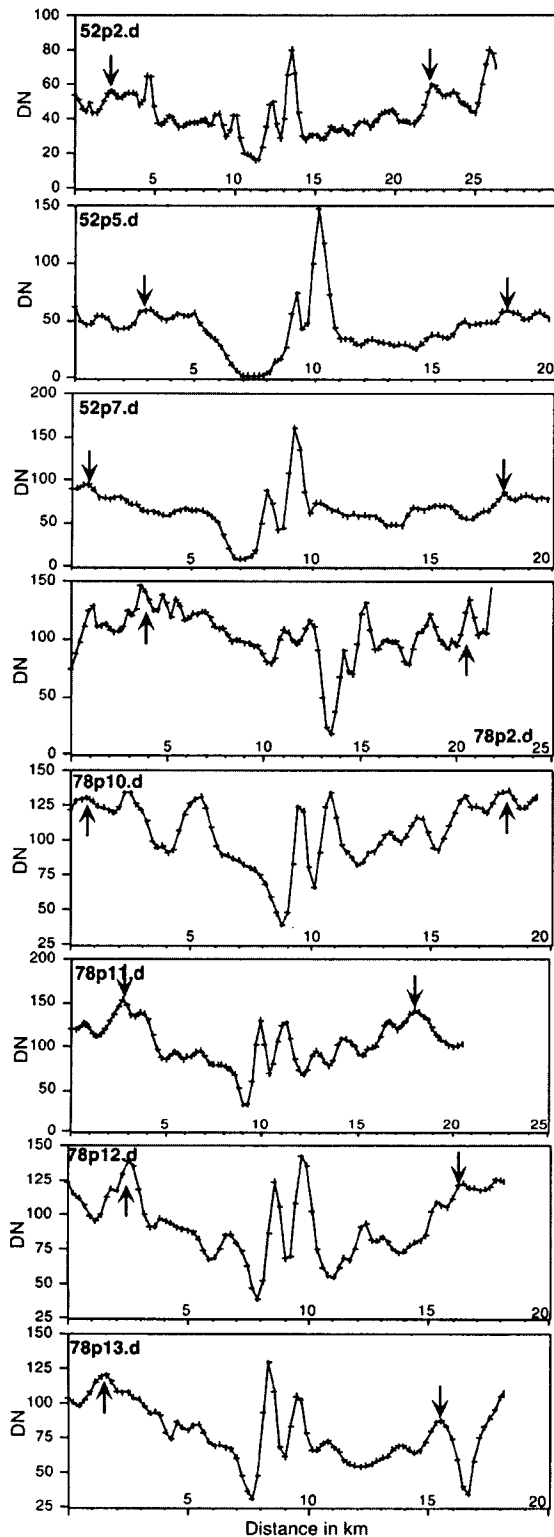
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Figure 2. DN brightness profiles for triple bands present in E17 images. Arrows depict outer margins of dark deposit.

2. Data Analysis

Under this study we scrutinized all images from the Galileo primary mission and subsequent mission extensions (Galileo Europa Mission (GEM) and Galileo Millennium Mission (GMM)), in order to identify those images that contained triple bands or lenticulae at resolutions of ~200 m/pxl or better. Once the relevant images were identified, they were processed to repair compression artifacts, make radiometric and photometric corrections, reproject to orthographic projection, and assemble mosaics.

As a method of improving our visual determination of diffuse edges of triple band margins in images for which high incidence angles suppressed albedo variations, we employed a routine attached to the VICAR image processing suite that enables us to take profiles of DN variations perpendicular to the axis of the triple band. In combination with the images, these brightness profiles (Fig. 2), allow for more accurate determination of triple band widths. We made more than 30 new triple band measurements in this way, yielding a total of ~80 profiles measured. The measurements yielded triple band widths from 13 to 25 km. We also looked for a correlation with latitude, with the idea that differences in ice temperature and thickness would be manifested in triple band sizes. However, we found no clear correlation suggesting that (i) triple bands formed over a range of time periods. (ii) ice heterogeneities (properties, composition, thickness?) on local to regional scales influence triple band formation.

We also performed detailed mapping at particularly clear examples of triple bands and lenticulae in order to assess the geological relationships and aid interpretation of their origins. For the triple bands, our continued observations suggest that thermally induced structural ice changes (lag deposits or annealing) are indeed the preferred explanation for the deposits. Although similar processes also appear to operate at the lenticulae, there also appear to be some cases for which fluid release at the surface
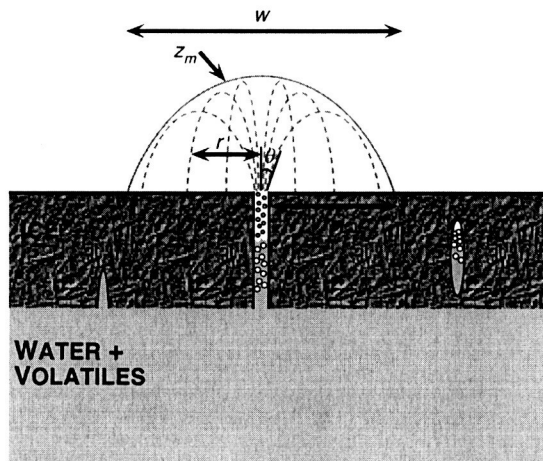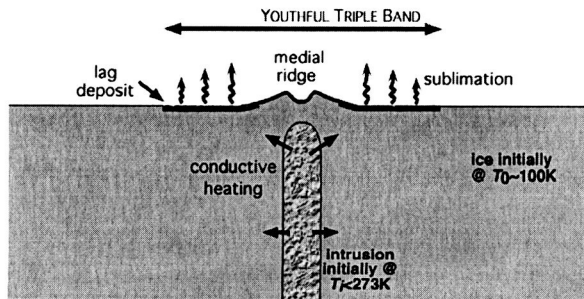
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Figure 3. Schematic representation of explosive venting from a volatile-bearing liquid layer beneath the surface ice.

from deposition of dark non-ice impurities.

may have taken place, perhaps by mobilization and release of near-surface brines [*Head and Pappalardo*, 1999].

3. Theoretical Modeling

Explosive Cryovolcanism

One possibility for the formation of dark deposits involves venting of material from a subsurface liquid body via exsolution and expansion of gases dissolved within the water (Fig. 3). If a fracture opens between the surface and the liquid layer (and the surface of Europa is ubiquitously fractured), then decompression of the liquid layer would allow the gases to escape, entraining droplets of the liquid phase and perhaps solid particles derived from the conduit walls. The dark surface would therefore result

We modeled the ballistic ejection of a gas-rich spray from the subsurface using equation (1):

$$w = \frac{8nRT_i\gamma}{mg(\gamma - 1)}\sin\theta\cos\theta \qquad (1),$$

which relates the deposit width, w, to the spread angle of the plume, θ, (Fig. 3), the initial temperature of the liquid/gas mixture, T_i, the mass fraction of gas in the erupted material, n, and the molecular weight of the volatile species, m. Here R is the universal gas constant, γ is the ratio of the specific heats of the gas, and g is acceleration due to gravity.

Application of this equation under Europan conditions and a variety of plausible volatile species (CO_2, CO, SO_2, NH_3) showed that 1 to 6 wt% dissolved volatiles are required to produced observed deposit widths up to 25 km. The corresponding eruption velocities range up to 250 m/s, and produce plumes up to 25 km high. These should be readily detectable in Galileo images of Europa's limb, but as yet, no plumes have been detected in such observations.

This implies either that we simply have

(a) Single intrusive body producing simple doublet ridge

(b) Multiple intrusions producing complex medial ridge system

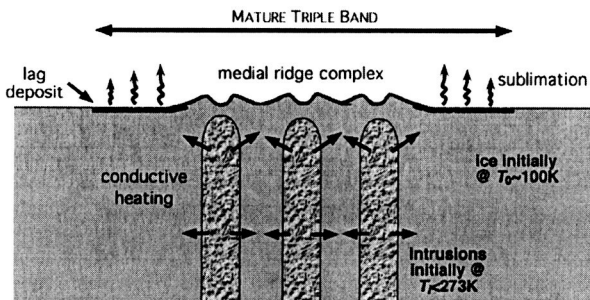**Figure 4.** Formation of triple bands by intrusions of, and heating by, warm ice, and subsequent lag deposit formation.

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not captured triple bands in the process of formation (perhaps they form rarely, or are no longer actively forming), or that explosive venting is an unlikely mechanism of formation of the triple bands. While we cannot rule this mechanism out, there is no compelling evidence to suggest it operates on Europa.

Cryomagmatic Intrusions

Our initial work suggested that intrusions of warm ice diapirs (~270 K) into the cold surface ice layers (~100 K) could reasonably explain the dimensions of dark lenticulae haloes and the smaller triple bands (<10 km width) [*Fagents et al.*, 2000]. However, intrusions as large as 2 km lose their thermal energy before bands (25 km width) could form. To address this issue, we suggested that (i) multiple or (ii) liquid intrusions might be required.

We addressed case (i) by implementing computational fluid dynamic simulations of multiple discrete intrusions, which then heat the surrounding ice. We found that indeed, intrusions repeated in space or time could provide significant additional energy to heat the surrounding ice and induce larger triple band margins (via sublimation lag deposit formation or ice annealing) (Fig. 5).
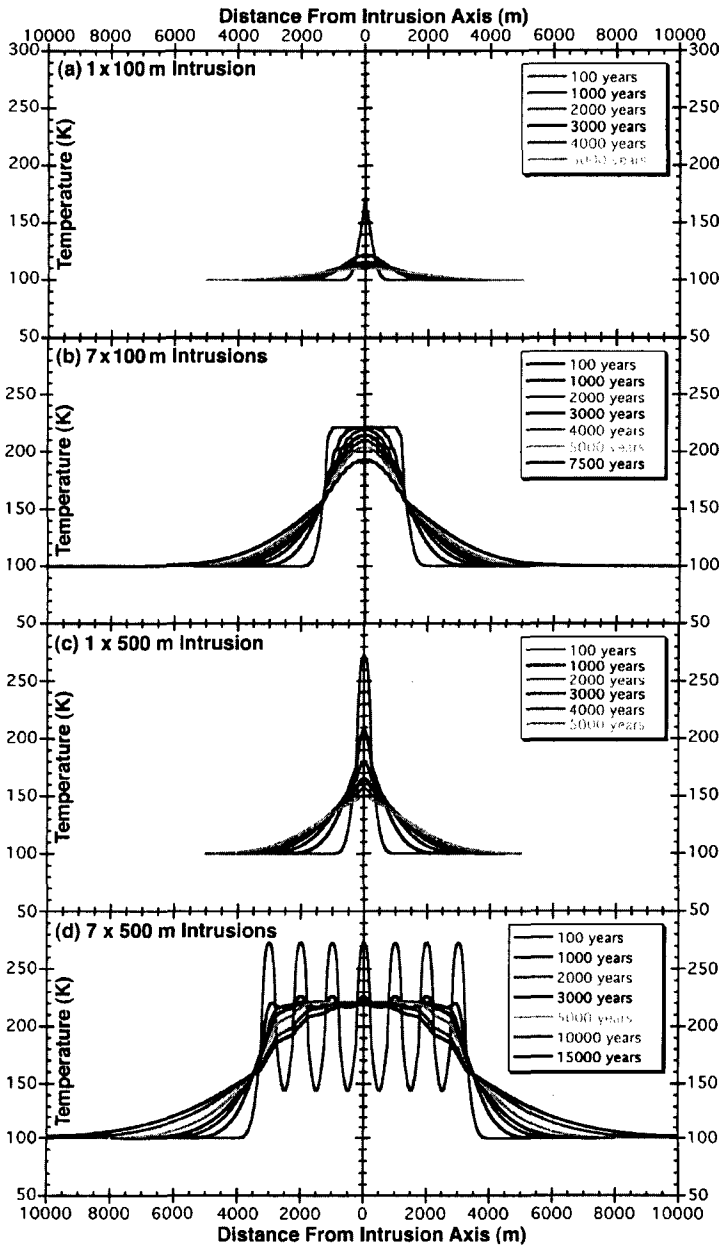

Figure 5. Numerical results illustrating enhanced heating of surface ice by multiple intrusive events.

However, the larger bands form more readily by repeated intrusion of liquid water, which could circulate and provide additional advective heating (essentially a constant temperature boundary condition on the ice wall), or could freeze and provide additional energy in the form of latent heat. Either case has significant thermal advantages of over the intrusion of solid ice. As indicated by Figure 6, liquid water circulating in an open fracture could heat the surrounding ice indefinitely, as long it was maintained in a liquid state (if, for example, the facture was connected to a global ocean at some depth).
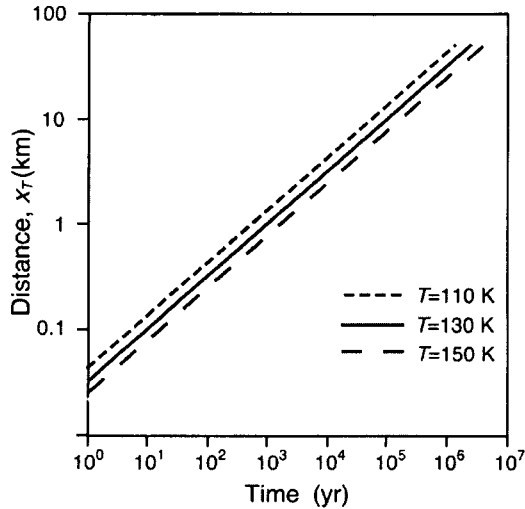
Figure 6. Lateral extent of ice heated by liquid 'intrusion' as a function of time. Different lines represent the lateral distance from the intrusion axis to the given isotherm.
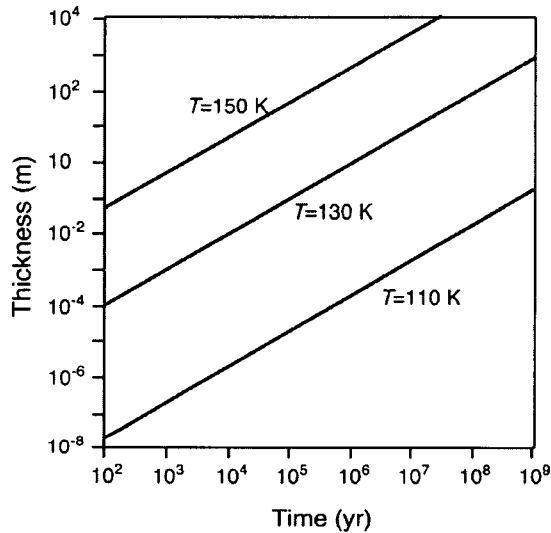

Figure 7. Thickness of ice sublimed as a function of time. Note the strong temperature dependence of sublimation rate.

Once the surface ice has been heated above a threshold temperature (130 K; [*Purves and Pilcher*, 1980; *Shoemaker et al.*, 1982; *Squyres*, 1980]), sublimation is enhanced, which promotes loss of ice and the formation of a lag deposit of non-ice material which remains behind at the surface. If the non-ice material is dark (e.g., a silicate mineral), only a fraction of percent by weight [*Clark and Lucey*, 1984] is required to produce a detectably darker surface. Furthermore, once the surface begins to darken, it will absorb more solar insolation and become warmer, this further enhancing sublimation. In this way, a feedback process is initiated, which leads to runaway sublimation to the point where the lag deposit armors the surface and prevents further ice loss [*Spencer*, 1987].

In Figure 7 we plot the results of our calculations on the thickness of ice that can be sublimed as a function of time and surface temperature. It is clear that once surface temperature exceed 130 K, significant ice removal is achieved on very short timescales, far less than the times required to heat the ice in the first instance, and insignificant on a geologic timescale.

4. Conclusions

We have modeled the formation of Europan triple bands and lenticulae halos by two processes: (i) explosive venting of cryoclastic material from a liquid layer in the Europan interior, and (ii) lag deposit formation by the thermal influence of subsurface cryomagmatic intrusions. We favor the latter hypothesis for explaining these features, and further suggest that a liquid water or brine intrusion is required to provide sufficient lateral heating of surface ice to explain the 25 km size of the largest features. (Solid ice diapirs, even under the most favorable conditions, become thermally exhausted before they heat significant lateral distances). We argue that water circulating in open fractures, or repeated cryomagmatic 'diking' events would provide sufficient thermal input to produce the observed features. Thus our work argues for the existence of a liquid beneath Europa's surface. Our results might most easily be explained by the presence of a continuous liquid layer (the putative Europan ocean); this would concur with the findings of the Galileo magnetometer team [*Kivelson et al.*, 2000]. However, we cannot rule out the possibility that discrete liquid pockets provide injections of fluid closer to the surface.

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6. Publications and Presentations

The following are the direct result of work completed under this grant:

Fagents, S.A. Considerations for effusive cryovolcanism on Europa. *Submitted to J. Geophys. Res.*

Fagents, S.A., and R. Greeley. Modeling intrusive processes in Europa's ice lithosphere. *Lunar Planet. Sci. Conf., XXXII, #1383,* 2001 (**attached**)

Fagents, S.A., R. Greeley, R.J. Sullivan, R.T. Pappalardo, and L.M. Prockter. Cryomagmatic mechanisms for the formation of Rhadamanthys Linea, triple band margins, and other low albedo features on Europa. *Icarus, 144,* 54-88, 2000.

Phillips, C.B., A.S. McEwen, G.V. Hoppa, S.A. Fagents, R. Greeley, J.E. Klemaszewski, R.T.

Pappalardo, K.P. Klaasen, and H.H. Breneman. The search for current geologic activity on Europa, *J. Geophys. Res.*, *105*, 22,579-22,598, 2000.

Pinkerton, H., S.A. Fagents, L.M. Prockter, P.M. Schenk, and D.A. Williams. Exotic lava flows, *in Environmental Effects on Volcanic Eruptions: From Deep Ocean to Deep Space,* (J.R. Zimbelman and T.K.P. Gregg, eds.), pp. 207-241, Plenum, Kluwer Academic/Plenum Publishers, 2000.

Invited Lecture: Some Considerations for Cryovolcanism on Europa. University of Arizona, Lunar and Planetary Laboratory, Tucson, AZ, October 2001.

Presentation: Modeling Intrusive Processes in Europa's Ice Lithosphere. Lunar and Planetary Science Conference, Houston, TX, March 2001

MODELING INTRUSIVE PROCESSES IN EUROPA'S ICE LITHOSPHERE.

S. A. Fagents and R. Greeley[1], [1]Department of Geological Sciences, Arizona State University, Tempe, AZ 85287; fagents@asu.edu.

Introduction: Europa is characterized by a wide variety of structural and albedo features which represent the surface manifestation of heat and mass transport within the ice lithosphere. Such features include triple bands, which exhibit medial ridges flanked by low-albedo margins (Fig. 1), and lenticulae comprising inner dome-like masses surrounded by dark haloes. Some of the dark surfaces exhibit structural control and might represent fluids released at the surface [1]. Others have diffuse margins and might represent a sublimation lag deposit [2]. In either case, a source of heat is implied, and through image analysis and modeling, we can make some inferences about the advective and diffusive processes within the lithosphere and the consequences for surface geology.

Thermal Processes in the Ice Lithosphere: We are exploring the ways in which various endogenic surface features might be produced, and determining the implications for the presence or absence of an extensive subsurface layer of liquid water.

Our initial modeling [2] investigated the consequences of diapiric intrusions of warm ice, in either a tabular configuration representative of intrusion beneath the medial ridge of a triple band (Fig. 2; [3]), or as a cylindrical plug responsible for the central updoming of some lenticulae [4,5,6]. Heating of the lithosphere by the warm diapir would promote enhanced ice sublimation at the surface [7-9], leaving a lag deposit of dark non-ice material.
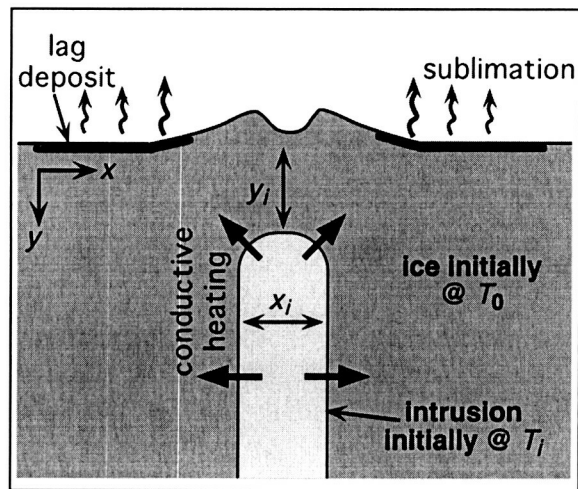

Figure 2. Proposed model for the formation of dark margins associated with triple bands.

Sublimation timescales are extremely short compared to the time required for the ice to be heated. Once the sublimation commences and the surface starts to darken, a positive feedback ensues, whereby darker surfaces absorb more solar radiation, becomes warmer and promotes increasingly rapid sublimation [9]. This continues until an armor of non-ice material suppresses further sublimation.

The results of the initial models suggest that dark margins a few kilometers wide can be produced by ~1 km wide warm ice intrusions within 10^4 to 10^5 years.

However, such a simple intrusion mechanism is incapable of producing the larger triple bands, which range in size up to ~25 km; the thermal energy of the intrusion is exhausted before a sufficient volume of lithospheric ice is heated.

Improvements to Models: To investigate the problem further we have made a number of improve-

Figure 1. Portion of Galileo imaging observation E17REGMAP01 showing two prominent triple bands displaying multiple medial ridge sets. A younger, less developed lineament crosscuts these bands. Incipient dark margins can be seen on this younger feature (arrows). The width of the largest band at profile A-A' is ~20 km.

INTRUSIONS ON EUROPA: S. A. Fagents and R. Greeley

ments in the model. First, algorithms were developed to describe the temperature-dependent behavior of ice thermophysical properties such as thermal conductivity and specific heat.

Next, we investigated the thermal consequences of the emplacement of multiple intrusions. This might be a reasonable model for the development of the largest triple bands, which have multiple medial ridge sets (Fig. 1), each of which might represent an individual intrusion.

Finally, we are currently investigating the influence of a global ocean of varying sizes, by applying lithospheric temperature gradients ranging from ~150 K/km to <1 K/km, representing end members of a thin ice shell overlying a thick water layer, and a 100 km thick solid ice lithosphere, respectively.

Results:

Thermophysical properties. The specific heat capacity of ice has a positive dependence on temperature [10], whereas thermal conductivity decreases with increasing temperature [11]. Previously, we had adopted constant values based on the intrusion and ice initial temperatures. When temperature-dependent formulations are included in the simulations for both the intruded body and the lithospheric ice, the net effect is to increase temperatures close to the intrusive contact by up to 10 K with respect to the previous simulations after a heating period of 50 years. At greater distances (>0.5 km), the ice properties approach the constant values adopted in the previous simulations, and the temperatures become similar. However, with increasing time, the effect of the temperature-dependent properties becomes more important at greater distances.

Multiple intrusions. The additional thermal energy provided by the multiple intrusions is capable of heating a much greater lateral extent of the ice surface. Figure 3 shows that two 100 m wide intrusions spaced a distance of 100 m apart are capable of almost doubling the lateral distance of ice heated above the threshold for enhanced sublimation (130 K [7,8]) after a heating period of 50 years, as compared to a single ice body.

Discussion: The modeling described above focuses on solid state bodies only (e.g., warm ice diapirs). Although simulations of multiple intrusions are promising for explaining features larger than a few km in width, there may be a need to advocate liquid intrusions to produce the largest features. This could correspond to liquid injected into the near surface from larger liquid body at depth. The additional heat pulse provided by the latent heat of crystallization might heat greater extents of surface ice. Alternatively, fractures connected to a global ocean could permit tidally driven cyclic injection of water into the ice lithosphere [12].

In addition to latent heat, this mechanism could provide additional thermal energy through the circulation ad replenishment of water in the fracture. There is now good evidence from Galileo's magnetometer instrument [13] to complement the geological evidence [14] for an ocean on Europa. Therefore, the consequences of liquid intrusions will be the focus of our next suite of simulations.
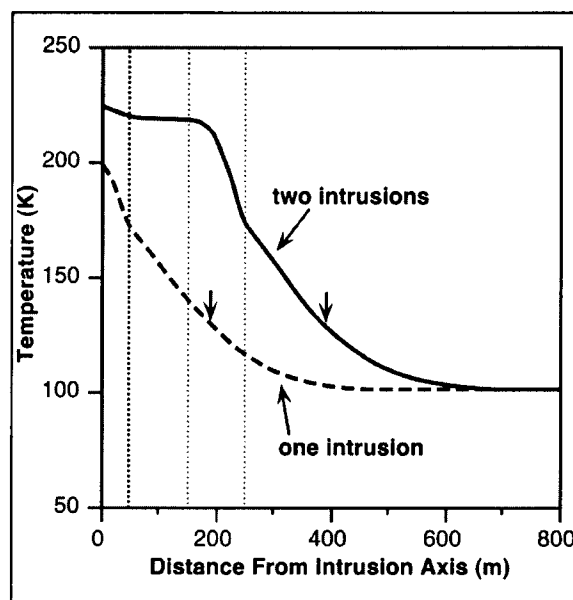

Figure 3. Temperature plotted as a function of distance after a heating period of 50 years for a single intrusion (dashed curve), and two intrusions separated by 100 m (solid curve). Initial temperature is 273 K. Vertical gray bars depict location and size of intrusive bodies; vertical arrows indicate lateral limits of enhanced sublimation ($T>130$ K) for each case.

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